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Vegetation diversity and habitat suitability modeling of the invasive plant *Bellucia pentamera* in conservation forests of West Sumatra, Indonesia

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Abstract. *Solfiyeni S, Fadhlan A, Aziz A, Syahputra G, Azzahra A, Mildawati M. 2024. Vegetation diversity and habitat suitability modeling of the invasive plant* Bellucia pentamera *in Conservation Forests of West Sumatra, Indonesia. Biodiversitas 25: 781-791.* The invasive plant *Bellucia pentamera* has spread to several regions in Indonesia, including the province of West Sumatra. Mapping the distribution of this invasive plant needs to be done to facilitate its management. offers a comprehensive approach to delineate the potential ecological range of a species and assess habitat suitability. This study aimed to evaluate the impact of *B. pentamera* invasion on vegetation diversity, conduct potential distribution mapping, and assess *B. pentamera* habitat suitability in West Sumatra conservation forests. The study utilized observational methods to determine coordinate points for *B. pentamera* presence and conducted vegetation analysis. The results from the vegetation analysis revealed disparities in composition and structure across three study areas, with diversity indices ranging from 2.60 to 3.84. The similarity index between study areas was relatively low, below 50%. The MaxEnt analysis delineated suitable locations for *B. pentamera* using the ROC curve (AUC) model, yielding values of 0.947 for training data and 0.923 for testing data. MaxEnt modeling identified suitable habitat for *B. pentamera* concentrated at Lima Puluh Kota, Tanah Datar, Padang, Solok and South Solok districts. This study's findings indicate a broad distribution of this species, with over 5% of the habitat deemed suitable for *B. pentamera*.

Keywords: Bioclimatic factors, composition and structure, invasive species, MaxEnt, species distribution modeling

Abbreviations: ANDA: Herbarium Andalas, ArcGis: Aeronautical Reconnaissance Coverage Geographic Information System, GPS: Global Positioning System, KBT: Hutan Kapalo Banda Taram, MaxEnt: Maximum Entropy, QGis: Quantum Geographic Information System, Tahura: Taman Hutan Raya

INTRODUCTION

The spread of invasive species poses a significant threat to biodiversity following habitat degradation (Simberloff et al. 2013). Internationally, the issue of invasive alien species has garnered attention due to their detrimental impacts on native species, habitats, and ecosystem functions. When invaders possess substantial competitive potential, leading to the displacement of resident species, the impact on plant diversity can be particularly negative. This competition from invasive plants can drive ecosystem modifications, profoundly affecting plant communities and exacerbating the impact of biological invasions (Kalusová et al. 2014; Carboni et al. 2021).

Invasive plant species disrupt ecosystem balance through aggressive dominance, resulting in diminished environmental quality, altered community composition and short-and long-term impacts on biodiversity (Srivastava et al. 2014; Tjittrosoedirdjo et al. 2016; Wahyuni et al. 2016; Ormsby and Brenton-Rule 2017). Understanding the extent of invasion by alien plants, including measures of their presence and abundance in plant communities, is essential for effective decision-making regarding their management (Catford et al. 2012; Guo et al. 2015; Gallardo et al. 2019).

One such invasive plant species of concern in Indonesia is *Bellucia pentamera* Naudin (Family Melastomataceae), originating from South America. *Bellucia pentamera* has spread to various regions in Indonesia, including Bogor, Sukabumi, South Sumatra, Jambi, West Sumatra, and West Kalimantan (De Kok et al. 2015; Lee et al. 2015; Lindsell et al. 2015; Suwardi et al. 2023). As a pioneer tree species with rapid growth, *B. pentamera* has the ability to quickly colonize forest gaps caused by fallen trees or logging, altering forest structure and forming a monodominant canopy (Dillis et al. 2017). This plant dominates high conservation value forests in PT. Kencana Sawit Indonesia, impacting plant diversity, microclimate, and soil conditions, with distribution patterns varying from clustered, random, to regular, according to existing forest gap conditions (Solfiyeni et al. 2022a; 2022b).

Given its invasive nature, mapping the spread of *B. pentamera* and assessing habitat suitability are critical for effective management, particularly in conservation forests. MaxEnt modeling offers a method for predicting species distributions, often used to forecast plant invasions across large geographic scales using event records and environmental factors (Wan et al. 2019). This approach provides a comprehensive understanding of a species' potential range and habitat suitability. Studies shown the accuracy of MaxEnt model to be more than 0.90, making it suitable for predicting plant distributions under current and future climate change scenarios (Xiong et al. 2019; Shen et al. 2022). MaxEnt has been successfully applied to predict potential distribution of various plant species, including *Hevea brasiliensis* in India (Ray et al. 2018) and *Calliandra calothyrsus* on Bali Island, Indonesia (Yudaputra 2020).

Studying the ecological aspects of *B. pentamera* is crucial for developing management strategies to reduce its dominance and promote timely recovery of native biodiversity. This study aimed to analyze the impact of *B. pentamera* invasion on vegetation diversity and assess its habitat suitability in West Sumatra conservation forest areas based on MaxEnt modeling.

MATERIALS AND METHODS

Study area

The study was conducted from April to September 2023 in the conservation forest area of Taman Hutan Raya Bung Hatta (Tahura), West Sumatra province with coordinate points (0°56'55.4"S and 100°30'49"E), altitude 450 meters above sea level (m asl), having temperature of 24°C, humidity of 84%, rainfall of 4437 mm/year; Cagar Alam Lembah Harau (0°02'46.3"S and 100°40'29.2"E) altitude 650 m asl, having temperature of 24°C, humidity of 72%, rainfall of 2089 mm/year and Kapalo Banda Taram Forest (KBT) at coordinate point (0°11'32.496"S and 100°43'28525"E) altitude 850 m asl, having temperature of 30.5°C, humidity of 65%, rainfall of 2089 mm/year (Figure 1). Plant identification was carried out at Herbarium ANDA, Universitas Andalas.

Data collection

The vegetation analysis was carried out using the quadratic method. A single plot measuring 20×50 meters was established at each study site using purposive sampling. The plot was subdivided into 10 subplots, each measuring 10 × 10 meters. Within each subplot, plant species were observed at the tree level, including species identification, Diameter at Breast Height (DBH) measurement, and counting the number of individuals for each species. Any unidentified plant species encountered in the field were collected to create herbarium specimens, which were subsequently identified at the Herbarium ANDA at Universitas Andalas.

Field observations were employed for vegetation mapping and analysis. Data for potential distribution mapping was collected by recording of the occurrence coordinates of invasive plant species *B. pentamera* along the observation route. Coordinates were recorded in the field at 82 points across all survey areas using GPS.

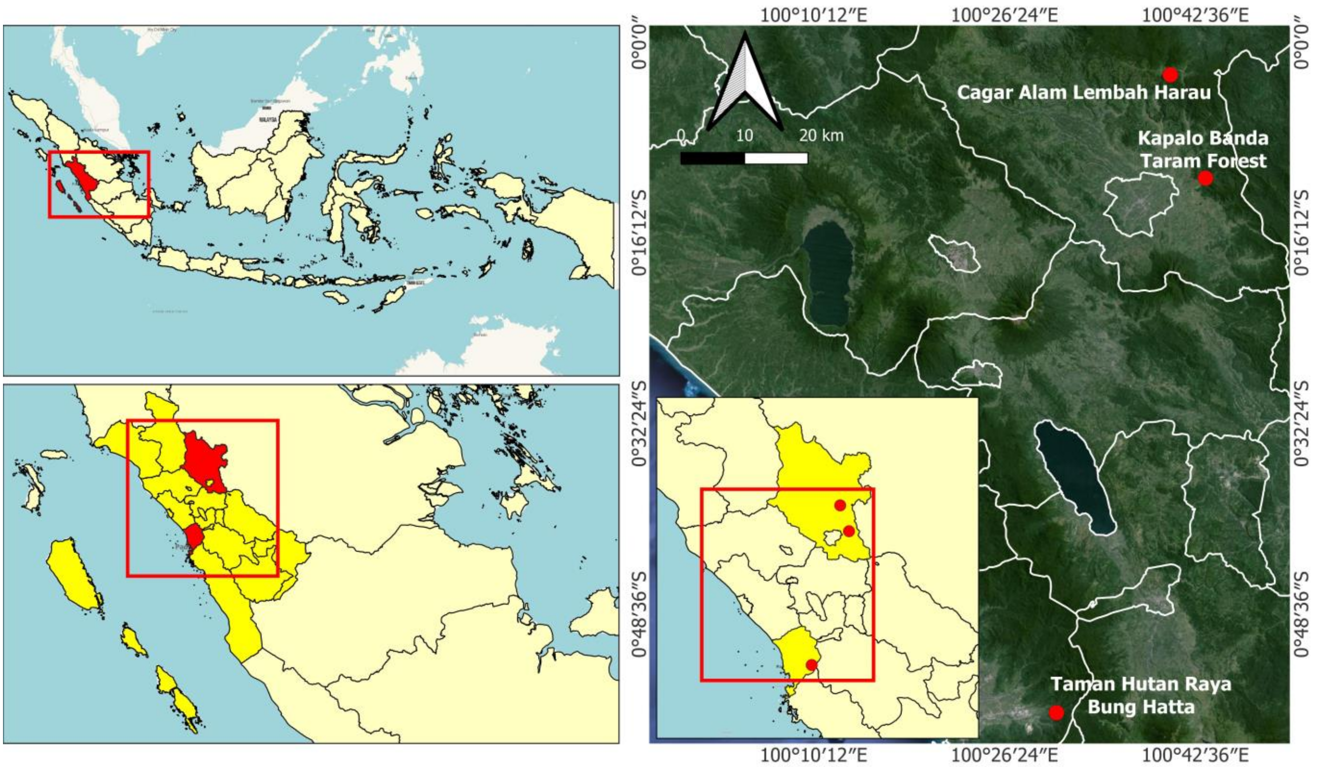

Figure 1. The map of study areas at Taman Hutan Raya Bung Hatta, Cagar Alam Lembah Harau and Kapalo Banda Taram, West Sumatra Province, Indonesia

Data analysis

Vegetation analysis

Microsoft Excel 2010 and Origin 2022 were used to examine the composition, structure, Shannon-Wiener diversity index, and Sorensen similarity index of the vegetation. The following formula was used to calculate the structure of the vegetation: Mueller-Dombois and Ellenberg (1974):

$$\text{Density} = \frac{\text{The number of a species}}{\text{Total area sampled}}$$

$$\text{Relative Density (RDi)} = \frac{\text{Density of a species}}{\text{Density of all species}} \times 100\%$$

$$\text{Frequency} = \frac{\text{Total plots of a species occurs}}{\text{Total number of plots used}}$$

$$\text{Relative Frequency (Rfi)} = \frac{\text{Frequency of a species}}{\text{Frequency of all species}} \times 100\%$$

$$\text{Domination} = \frac{\text{Basal area of a species}}{\text{Total area sample}}$$

$$\text{Relative Dominance (Rdo)} = \frac{\text{Dominance of a species}}{\text{Dominate of all species}} \times 100\%$$

Importance Value Index (IVI) = Relative Density (RDi) + Relative Frequency (RFi) + Relative Dominance (RDo)

Diversity index

The Shannon-Wiener Shanon Index (H') was used to determine the species diversity in each study area and calculated using the formula (Odum and Barrett 1971):

$$H' = -\sum \{(ni/N) \log (ni/N)\}$$

Where:
H' : Shannon diversity index
ni : Important value of each species
N : Total important value

The Diversity Index value according to Shannon-Wiener is defined as follows: (i) An H' value >3 indicates that species diversity is high. (ii) The value of H'<1<3 indicates that species diversity is classified as moderate. (iii) An H' value <1 indicates that species diversity is low.

Evenness index

The evenness of a species impacts its stability, with higher H' values indicating greater stability of diversity within the group. Conversely, lower H' values suggest a lower stability of species diversity within the community. Evenness refers to the relative abundance of different species in a community, and a more even ecosystem exhibits a more balanced distribution of abundance among species. Consequently, communities with higher levels of evenness and diversity tend to be more stable compared to those with lower levels of evenness and diversity (Sholiqin et al. 2021). The tree community structure in the study plot was analyzed through determination of the evenness index between species or the Evenness index (E') (Odum and Barrett 1971) through following formula:

$$E' = \frac{H'}{\text{Ln (S)}}$$

Where:
E' : Species evenness index
H' : Shannon diversity index
S : Number of types found
Ln : Natural logarithm

A higher value of E' indicates that the species in the community are distributed more evenly. Specifically, when E'<0.3, it indicates low species evenness, E' = 0.3-0.6 denotes medium species evenness, and E'>0.6 signifies high species evenness.

Dominance index

The dominance index was used to assess the concentration and distribution of dominant species. When dominance is concentrated in one type, the dominance index value increases, whereas if several types dominate together, the dominance index value would be low. To calculate the dominance index value, the equation proposed by Misra (1973), was utilized:

$$C = \sum_{I=1}^{n} \left(\frac{ni}{N}\right)^2$$

Where:
C : Dominance index
ni : Important value of each species
n : Total of all species
N : Total importance value of all species

Sorensen similarity index

The Sorensen Similarity Index (IS) was used to see the similarity index, which was calculated using the following equation (Misra 1973):

$$IS = \frac{2c}{a+b} \times 100\%$$

Where:
IS : Index Similarity
a : Number of species in community 1
b : Number of species in community 2
c : Total species in both communities

Environmental data variables

Modeling the habitat suitability and potential geographic distribution of *B. pentamera* involved utilizing 19 climate data variables with a resolution of 2.5 arc minutes (equivalent to 5 km at the equator) and altitude variables from the Coupled Model Intercomparison Project Phase 6 (CMIP6), obtained from the WorldClim database (Fick and Hijmans 2017; https://www.worldclim.org/). These climatic data variables are essential for conducting various ecological analyses, including delineating ecological niches, estimating global distribution prospects, and assessing the impact of climate change on future species distributions. Habitat distribution *B. pentamera* was determined using these 19 bioclimatic variables along with elevation data.

Maxent model

The geographical distribution of the plant *B. pentamera* was modeled using MaxEnt software ver. 3.3.3.e (Phillips et al. 2017), downloaded from the Biodiversity Informatics Program page (https://biodiversity informatics.amnh.org/) of the Center for Biodiversity and Conservation (CBC). Data of *B. pentamera* and environmental variables were loaded into the MaxEnt software. Parameters were configured with 25% of distribution points allocated for test data, 75% for training data, a maximum of 500 iterations, and a convergence threshold of 10^{-5}. Additionally, the analysis included the use of log response curve of the predictor variables, Jackknife testing, random seeded 10 repetitions, Multivariate Environment Surface Similarity (MESS) (Ali et al. 2023).

Accuracy validation

The accuracy of model predictions is assessed using Area Under the Curve (AUC) and True Skill Statistics (TSS). The evaluation criteria for model prediction accuracy were categorized into four groups: poor (AUC<0.80), fair (0.80≤AUC<0.90), good (0.90≤AUC<0.95), and excellent (0.95≤AUC≤1.00). TSS evaluates a model's overall accuracy relative to random accuracy, with a TSS score exceeding 0.5 indicating optimal performance (Silva et al. 2022).

Habitat suitability analysis

The MaxEnt output raster file was loaded into ArcGIS (version 10.8) and QGis (Version 3.28.2) software to classify habitat suitability and analyze spatial data. The habitat suitability *B. pentamera* was classified into four categories: very suitable habitat (0.7≤P≤1.0), suitable habitat (0.5≤P<0.7), less suitable habitat (0.2≤P<0.5), and unsuitable habitat (0.0≤P<0.2). Subsequently, the number of grids cells for each class was calculated to determine the extent of plant distribution (Huang et al. 2022).

RESULTS AND DISCUSSION

Vegetation composition and structure

The vegetation observations conducted at the three study areas revealed variations in vegetation composition and population sizes of *B. pentamera*. Differences in the number of *B. pentamera* individuals at each study area led to differences in the total number of local tree species. Specifically, at the Tahura location, four individuals of *B. pentamera* were recorded, alongside a total of 25 tree species. At the Lembah Harau location, five individual trees were identified, including *B. pentamera*, with total of 16 tree species recorded. Lastly, at the KBT location, 13 species and seven individuals of *B. pentamera* were observed. The species composition at each location is illustrated in Figure 2.

Invasive plants, such as *B. pentamera*, have become widespread in the study area, especially in the KBT forest. Despite only seven individuals being found in the observation plot, this invasive species was frequently encountered outside the forest area and along the KBT tourist route. Additional factors contributing to its prevalence include the favorable conditions near the river, as the KBT location serves as a water catchment area that fosters growth and doubles fruit production. Dillis et al. (2018) noted that *B. pentamera* trees growing beside rivers can produce twice as much fruit as those located farther away.

The presence of the invasive plant *B. pentamera* exerted varying influences on the composition and structure of vegetation at the three observation locations. Study conducted at these locations found a correlation between the number of *B. pentamera* individuals and the diversity of local tree species; areas with higher numbers of *B. pentamera* tended to have fewer tree species. The species composition at each location can be seen in Figure 2. Specifically, in the observation plot at Tahura, there were four *B. pentamera* individuals and 25 local tree species. In Lembah Harau, five individuals of *B. pentamera* were observed along with 16 local tree species, while in KBT, seven individuals of *B. pentamera* were found alongside 13 local tree species. The number of species observed in this study aligns closely with the findings of Solfiyeni et al. (2022a), who reported 23 plant species in locations dominated by *B. pentamera* in the conservation forest of PT. Kencana Sawit Indonesian. However, the number of species observed at Lembah Harau and KBT locations tended to be lower than that at the Tahura location. This discrepancy may be attributed to the competitive nature of *B. pentamera*, which can outcompete local species, leading to a reduction in their abundance. Additionally, differences in abiotic factors such as temperature, humidity, light intensity, and altitude (Table 3) also influence vegetation composition at each location.

Furthermore, the composition and structure of vegetation at each location can also influence abiotic factors such as temperature, humidity, and light intensity. The introduction of invasive species triggers intense competition among various species competing for the same resources. Species with limited adaptations in acquiring these resources, typically those lower in the competitive hierarchy, are often displaced by more competitive species. These superior competitors leverage various mechanisms to gain a competitive edge, including below-ground conflicts, chemical interactions (allelopathy), and the mediation of the microbiome. Consequently, these alterations ripple through the ecosystem, reshaping competitive hierarchies within the affected environment (Carboni et al. 2021).

As the number of *B. pentamera* individuals increases, the number of tree species tends to decrease. This trend may also be attributed to the characteristics of *B. pentamera*, such as rapid growth, prolific fruit and seed production, and production of allelochemical compounds such as phenols and flavonoids (Solfiyeni 2022), which negatively affect seed germination and root elongation (Tanase et al. 2019).

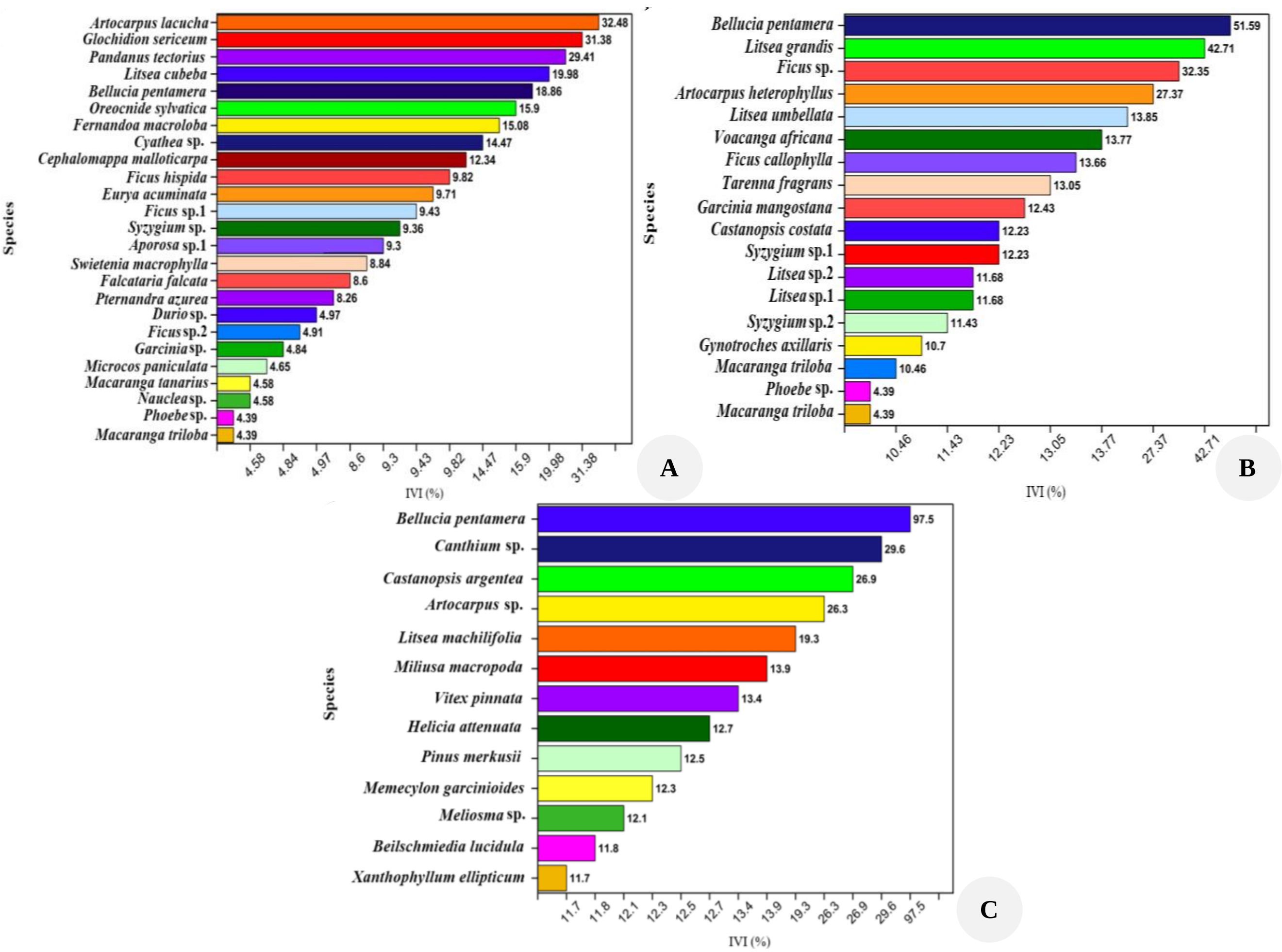

Figure 2. A. Composition of 25 tree species in Taman Hutan Bung Hatta, B. Composition of 16 tree species in the Lembah Harau, C. Composition of 13 tree species in the Kapalo Banda Taram forest of West Sumatra, Indonesia

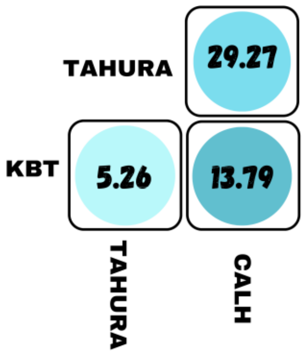

Figure 3. Sorensen similarity index (%) of tree vegetation between study areas Tahura, Lembah Harau (CALH) and Kapalo Banda Taram (KBT) of West Sumatra, Indonesia

Differences in the number of tree species at each location also influenced the similarity index. The Sorensen similarity index values for the three locations are depicted in Figure 3. Notably, the similarity index between study areas for tree categories in the three conservation forest areas exhibited varying and relatively low values. These discrepancies are likely attributable to differences in environmental conditions across each area. The species similarity index was deemed insignificant as it fell below 50% (Mueller-Dombois and Elleberg 1974). Plant diversity was found to be profoundly influenced by spatial and temporal factors, with optimum temperature, humidity, and rainfall exerting significant control. This influence of temperature, humidity, and precipitation on diversity was particularly evident when considering taxonomic diversity (species richness) at broad spatial scales. Globally, regions characterized by warm and wet climates tend to support more species compared to regions with cold or arid climates (Rundel et al. 2016).

Table 1 presents the tree-level vegetation structure, including Relative Density (RDi), Relative Frequency (RFi), Relative Dominance (RDo), and Importance Value Index (IVI), observed at the three locations. Notably, *B. pentamera* dominated in two locations, namely the Harau Valley Nature Reserve and the Kapalo Banda Taram area, with INPs of 51.9% and 97.50%, respectively. The table also lists the ten main types of tree vegetation based on the highest INP observed in each study area.

Furthermore, the three study areas exhibit varying diversity indices, ranging from 2.26 to 3.84, indicating medium to high diversity levels. The species Diversity

Index (H') value serves as a measure of the stability of species diversity within a community. Additionally, the Evenness Index (E') and the Dominance Index (C) values provide insights into the concentration and distribution of dominant species, contributing to the assessment of species stability. Table 2 displays the diversity index, evenness index, and dominance index values for each study area. Notably, the evenness index value at the Tahura location is higher than at the other two locations, suggesting a more evenly spread distribution of species within the community. Conversely, the dominance index value at the KBT location exceeded that of the Lembah Harau and Tahura locations, indicating that the community at KBT to be centered around one dominant species, namely *B. pentamera*, which exhibited the highest relative density, relative frequency, and relative dominance within that location.

Table 3 presents the results of measuring environmental factors, including air temperature, humidity, light intensity, and altitude in the study area. These measurements revealed differences in all abiotic factors, particularly altitude. Specifically, the air temperature recorded at the KBT location was higher compared to other two locations, corresponding with its higher altitude. According to theoretical expectations, higher altitudes typically correspond to lower temperatures. The elevated temperature at the KBT location may be attributed to be sparse tree coverage in the study area, resulting in smaller canopy and higher intensity reaching the forest floor, accompanied by low air humidity.

Conversely, the Tahura location, characterized by the lowest altitude at 450 meters above sea level, exhibited lower air temperatures. This phenomenon is likely due to the more favorable forest conditions at Tahura, characterized by relatively high plant diversity (H'=3.84) and denser tree canopy cover. Consequently, the canopy cover at Tahura extended over a larger portion of the plot location, resulting in the reduced light intensity reaching the forest floor and maintaining lowers temperature and humidity levels. It is plausible that the presence of the invasive plant *B. Pentamera* indirectly influenced these abiotic factors. Prior research by Solfiyeni (2022) suggested that *Bellucia pentamera* releases allelochemical compounds in the form of phenols and flavonoids, from its roots and leaves, which may inhibit the growth of other plant species. Consequently, the proliferation of *B. pentamera* creates more open forest conditions, contributing to the observed higher temperatures at the KBT location compared to Tahura and Lembah Harau.

Table 1. Relative Density (RDi), Relative Frequency (RFi), Relative Dominance (RDo) and Important Value Index (IVI) of the ten most important species of tree vegetation on Tahura, LembahHarau and Kapalo Banda Taram of West Sumatra, Indonesia

Species	Family	RDi (%)	RFi (%)	RDo (%)	IVI (%)
Tahura					
Artocarpus lacucha Buch.-Ham.	Moraceae	3.85	4.55	24.09	32.48
Glochidion sericeum (Blume) Zoll. & Moritzi	Phyllanthaceae	3.85	4.55	22.99	31.38
Pandanus tectorius Parkinson	Pandanaceae	19.23	4.55	5.63	29.41
Litsea cubeba (Lour.) Pers.	Lauraceae	3.85	4.55	11.59	19.98
Bellucia pentamera Naudin	Melastomataceae	7.69	9.09	2.07	18.86
Oreocnide sylvatica (Blume) Miq.	Urticaceae	5.77	9.09	1.04	15.90
Fernandoa macroloba (Miq.) Steenis	Bignoniaceae	1.92	2.27	10.88	15.08
Cyathea sp.	Cyatheaceae	5.77	6.82	1.88	14.47
Cephalomappa malloticarpa J.J.Sm.	Euphorbiaceae	3.85	4.55	3.95	12.34
Ficus hispida L.f.	Moraceae	3.85	4.55	1.42	9.82
Lembah Harau					
Bellucia pentamera Naudin	Melastomataceae	21.74	15	14.85	51.59
Litsea grandis (Nees) Hook.f.	Lauraceae	13.04	10	19.67	42.71
Ficus sp.	Moraceae	8.70	10	13.66	32.35
Artocarpus heterophyllus Lam.	Moraceae	4.35	5	18.02	27.37
Litsea umbellata (Lour.) Merr.	Lauraceae	4.35	5	4.50	13.85
Voacanga africana Stapf	Apocynaceae	4.35	5	4.43	13.77
Ficus callophylla Blume	Moraceae	4.35	5	4.31	13.66
Tarenna fragrans (Blume) Koord. & Valeton	Rubiaceae	4.35	5	3.70	13.05
Garcinia mangostana L.	Clusiaceae	4.35	5	3.08	12.43
Syzygium sp.1	Myrtaceae	4.35	5	2.88	12.23
Kapalo Banda Taram (KBT)					
Bellucia pentamera Naudin	Melastomataceae	33.33	22.20	41.90	97.50
Canthium sp.	Rubiaceae	4.76	5.60	19.26	29.60
Castanopsis argentea (Blume) A.DC.	Fagaceae	9.52	11.10	6.28	26.90
Artocarpus sp.	Moraceae	9.52	11.10	5.69	26.30
Litsea machilifolia Gamble	Lauraceae	4.76	5.60	8.99	19.30
Miliusa macropoda Miq.	Annonaceae	4.76	5.60	3.60	13.90
Vitex pinnata L.	Lamiaceae	4.76	5.60	3.05	13.40
Helicia attenuata (Jack) Blume	Proteaceae	4.76	5.60	2.38	12.70
Pinus merkusii Jungh. & de Vriese	Pinaceae	4.76	5.60	2.21	12.50
Memecylon garcinioides Blume	Melastomataceae	4.76	5.60	1.97	12.30

Table 2. Diversity index, evenness index and dominance index at study areas invaded by invasive plants *B. pentamera*

Research sites	Species diversity index (H')	Evenness index (E')	Dominance index (C)
Tahura	3.84	1.19	0.12
Lembah Harau	2.60	0.94	0.09
KBT	2.26	0.88	0.15

Table 3. Results of measuring abiotic factors in the study area of West Sumatra, Indonesia

Research sites	Air temp. (°C)	Humidity (%)	Light intensity (%)	Altitude (masl)
Tahura	24	84	28.7	450
Lembah Harau	24	72	38	650
KBT	30.5	65	82.3	850

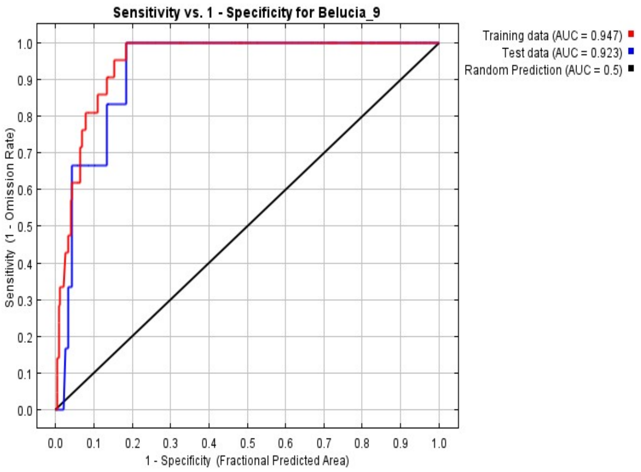

Figure 4. Receiver Operating Characteristic (ROC) curve for training and testing data with Area Under the ROC Curve (AUC)

Habitat suitability modeling

Field observations have revealed the widespread presence of *B. pentamera* across various areas, each exhibiting different population sizes. The coordinates of *B. pentamera* occurrences were further analyzed to model habitat suitability and potential geographic distribution using MaxEnt software. The modeling results demonstrated excellent model accuracy. Notably, the Area Under the ROC Curve (AUC) for the current model was relatively high, with values of 0.947 for training data and 0.923 for testing data. These results signify MaxEnt's superior capability in distinguishing suitable and unsuitable locations for *B. pentamera* (Figure 4). It is worth noting that in modeling species distributions, ROC analysis stands out as the most reliable indicator of model performance, offering broad applicability (Zhuang et al. 2018).

The data analysis conducted using MaxEnt demonstrates high credibility and precision. Figure 4 displays the ROC curve for *B. pentamera* through MaxEnt, revealing excellent model performance in the both training and testing datasets, with AUC values of 0. 947 and 0. 923, respectively. Notably, both upper left corners of the curve are close to 1, underlining the model's reliability and precision in predicting *B. pentamera* habitat suitability. In the case of random data partitioning, with 75% for training data and 25% for testing data, the model yields the highest AUC values for both training and testing data in the ROC Test. This random partition test, applied to *B. pentamera* occurrence data, effectively reduces significant prediction errors by creating distinct datasets for model validation through training and testing data. A logistic threshold value of 0.355 indicates perfect testing with 100% sensitivity and specificity, a fractional prediction area of 0.135, a training error rate of 0.143, and a testing error rate of 0.333, all based on the point closest to the upper left corner (0.1) on the ROC.

The *B. pentamera* model performance may be categorized into six levels: outstanding (0.90-1), good (0.80-0.90), fair (0.70-0.80), bad (0.60-0.70), and unsuccessful (0.50-0.60) (Liu et al. 2021). A low degree of omission is necessary in species distribution modeling to differentiate between climate-suitable and unsuitable sites and to avoid under- or overestimation of species abundance predictions (Bertrand et al. 2012). The inability to integrate significant environmental parameters in species distribution models can result in erroneous estimates of species distributions under future climate scenarios. By integrating all important environmental variables in species distribution models, it would be possible to predict better how species distributions may move in response to climate change. However, it was also important to balance incorporating environmental elements with the need for simple and easy-to-use species distribution models, as too complex models will be challenging to understand and implement in conservation management (Fernández et al. 2013).

Table 4 provides an estimation of the relative contribution of environmental components to the MaxEnt model. The initial estimate was calculated by adding the increase in controlled gain at each iteration of the training process to the to the contribution of the corresponding variable, or subtracting if the change in the absolute value of lambda was negative. For the second estimation, the values of each environmental variable in the training and background data were randomly swapped. The model was re-evaluated based on the shuffled data, and the decrease in training AUC is shown in a table, normalized to a percentage.

Based on the results of the analysis of environmental predictor variables through the Jackknife test obtained using the MaxEnt model (Table 4), it was evident that various climate factors significantly contribute to the distribution of *B. pentamera*. Seasonal rainfall, accounting for 16.8%, along with rainfall of the wettest month contributing 16.5%, and annual average temperature contributing 13.3%, emerged as the most influential factors. The distribution of *B. pentamera* in the study area appears to be primarily shaped by seasonal rainfall (Table 4), which ranges from 2066 to 2600 mm, followed by other environmental factors such as rainfall of the wettest month, average annual temperature etc. This suggests that seasonal rainfall, rainfall of the wettest month, and annual average temperature were the three primary limiting factors for the distribution of *B. pentamera* it the study area. According to study by Dillis et al. (2018), water sources significantly influenced the distribution of *B. pentamera*, with plants growing near rivers producing twice as much fruit, and exhibiting greater population density. Additionally, findings of Solfiyeni (2022) indicate that the spatial distribution of *B. pentamera* is closely linked to riverbanks, with higher densities observed nearer to rivers. Germination tests conducted by Solfiyeni (2022) revealed that *B. pentamera* germinates more successfully in moist soil conditions and low light intensity (25-50%). However, intraspecific competition among seedlings, particularly for space and light, can hinder their survival.

Rainfall played a significant role in shaping the presence and prevalence of invasive plant species, with alterations in the seasonal precipitation patterns due to climate change affecting their growth, survival, and reproductive success. The interplay between rainfall and invasive plant distribution is contingent upon temperature, soil nutrients, and competitive interactions (Kharivha et al. 2022). Generally, invasive plant species are expected to expand their distribution beyond their native habitats towards warmer areas in response to changes in climate conditions. Increased rainfall may exacerbate the impact of nitrogen addition on the performance of invasive plants in subtropical native communities (Li et al. 2022).

Changes in temperature and rainfall significantly influence plant distribution, with plants thriving in favorable conditions and struggling in unsuitable environments conditions over time. Invasive species like *Bellucia pentamera* prefer slightly shaded environments for germination, such as under the canopy of bushes or other plants, and exhibit rapid growth to compete for light with surrounding vegetation. A previous study of Solfiyeni et al. (2022a) suggests that the habitat of *B. pentamera* to be typically at the forest edge or within forest gaps, where higher light intensity and temperature prevail.

High levels of rainfall increase soil moisture, creating challenges for native species to compete with invasive ones. Invasive plants often possess robust root systems capable of absorbing considerable volumes of groundwater (Pfeiffer and Gorchov 2015). This aligns with the characteristics of *B. pentamera*, a tree species known for its rapid growth and competitive advantage over local pioneer tree species (Dillis et al. 2017). Figure 5 illustrates the influence of each environmental factor on the distribution of *B. pentamera* at the research site, with BIO 14 showing the most substantial impact when used alone, and BIO 15 emerging as the variable with the greatest influence on outcomes, containing unique information not present in the other variables.

Table 4. Estimated average contribution and importance of permutations of environmental variables used in MaxEnt modeling

Code	Variables	Percentage contribution (%)	Permutation importance
BIO 15	Seasonal rainfall	16.8	21.4
BIO 13	Wettest month rainfall	16.5	17.6
BIO 1	Annual average temperature	13.3	4.4
BIO 16	Rainfall in the wettest quarter	9.3	7.9
BIO 17	Rainfall in the driest region	8.2	12.3
BIO 12	Annual rainfall	6.5	11.1
BIO 4	Seasonal temperature	6.1	1.3
BIO 2	Diurnal average range (Monthly average)	5.9	0.6
BIO 19	Rainfall in the coldest quarter	5.7	0.1
BIO 9	Average Temperature of the driest quarter	3	5.8

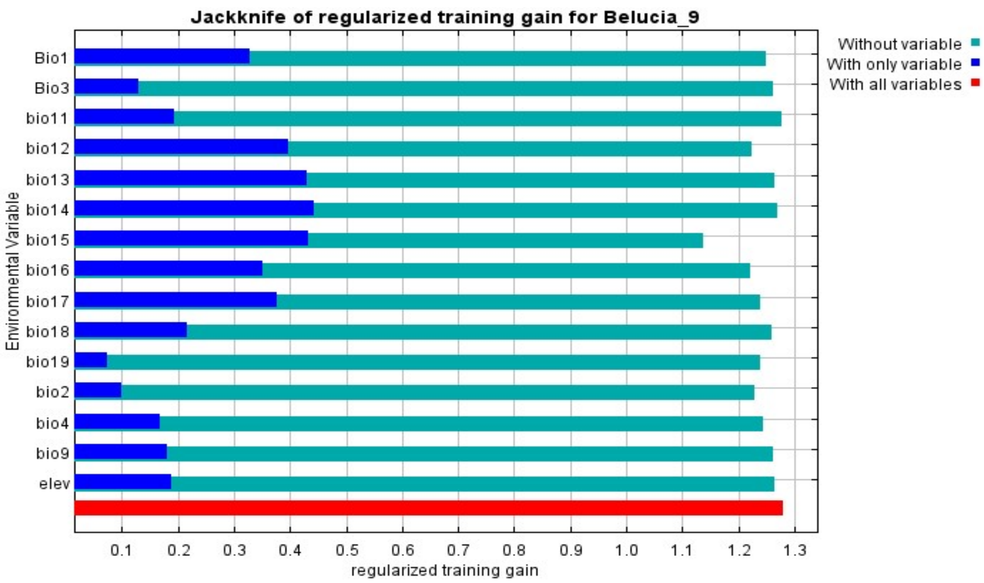

Figure 5. Jackknife test for the relative importance of environmental variables in MaxEnt model development

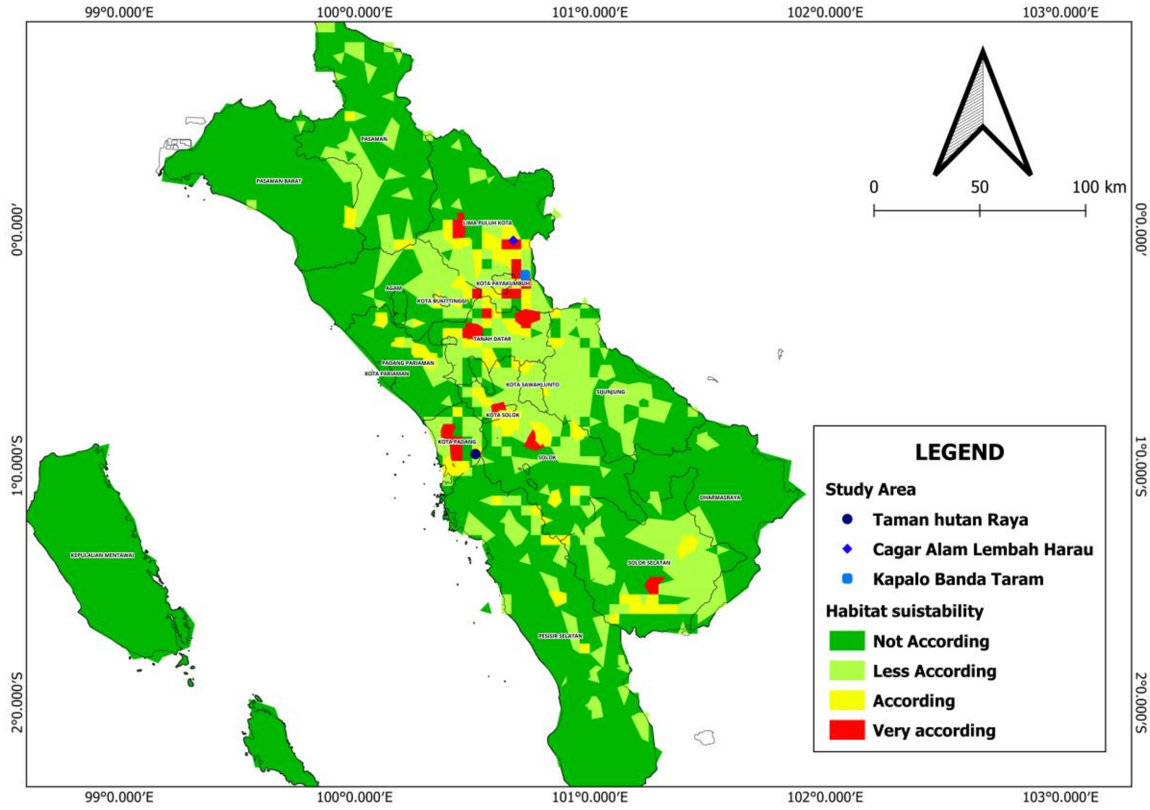

Figure 6. Map of habitat suitability and distribution potential *Bellucia pentamera* in West Sumatra, Indonesia

Observations and data collection conducted in the observed forest locations revealed the presence of invasive plants, particularly *B. pentamera*. The size of the population varied across these locations, reflecting differences in ecological impact, particularly on plant species composition and structure, which also varied from one region to another.

Modeling habitat suitability and plant distribution of *B. pentamera* revealed that certain habitats in West Sumatra province are suitable for its growth (Figure 6). Other important environmental variables determining the species distribution include altitude, rainfall, and temperature. Predictive maps help to identify areas with a physical environment similar to that of the species. Based on maps generated from MaxEnt and further processed in Qgis and Arc-Gis, the potential distribution of *B. pentamera* currently encompasses Lima Puluh Kota, Tanah Datar, Solok Selatan, and Padang districts, and primarily includes locations with altitudinal range of 400-900 meters above sea level. This aligns with *B. pentamera*'s typical habitat, found on hillsides, at forest edges, and in secondary forests (Solfiyeni et al. 2022a). Study of Moura and Vitorino (2018) on geographic distribution and habitat preferences indicates that *B. pentamera* exhibits high adaptability, rapid spread, and prolific seed production, with seeds persisting in the soil for extended periods. This species also favors disturbed habitats such as secondary forests and roadsides and can adapt across altitudinal gradients from lowlands to uplands, primarily favoring lowlands. The prediction map (Figure 6) of areas susceptible to invasion will aid in controlling and managing this invasive species.

MaxEnt can pinpoint areas where invasive species are likely to occur, guiding management efforts. Several studies have utilized MaxEnt to explore the distribution of invasive plant species and the environmental factors influencing their spread. Areas invaded by *B. pentamera* were characterized by higher temperatures and light intensity, along with increased soil nitrogen and phosphorus content. These factors can have complex and interacting effects on plant growth and development (Solfiyeni et al. 2022a). While higher temperatures and light intensity can promote photosynthesis and growth, excessive levels can induce stress and damage. It is crucial to develop effective management strategies by identifying areas conducive to the thriving of such plants. However, more data on the distribution of *B. pentamera* from this and previous ecological studies are needed, particularly in unobserved forest areas in West Sumatra. Further research is essential to gather comprehensive data for managing this invasive species in the future.

The conclusions drawn from this research on tree species diversity highlight differences across the three study areas. Greater numbers of individual *B. pentamera* trees corresponded to fewer species and lower species diversity index values. The modeling results align with the actual distribution area, with AUC values exceeding 0.9 in each period, indicating high accuracy. Environmental factors influencing *B. pentamera* distribution include seasonal rainfall, rainfall of the wettest month, and annual average temperature. MaxEnt modeling estimates the total suitable habitat for *B. pentamera* growth at 228,726 hectares, concentrated in Lima Puluh Kota, Tanah Datar, Padang, Solok, and Solok Selatan districts.

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